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PERSPECTIVE ON UNDERGROUND AND OBSCURED TARGET DETECTION AND IMAGING

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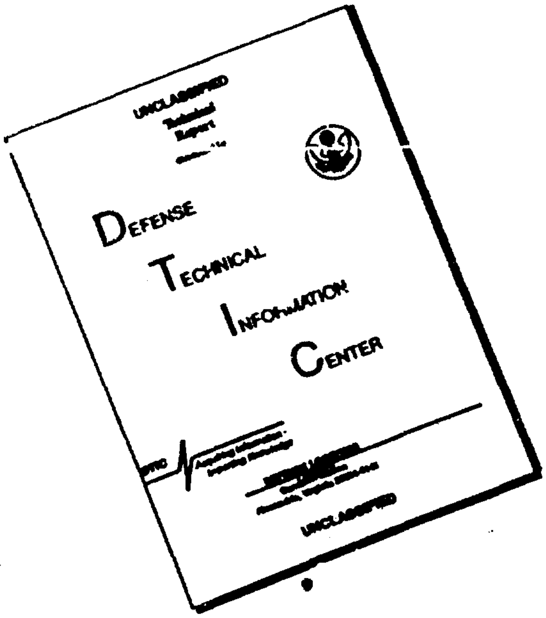

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This paper focuses on some of the work forming the background of today's state of the ground probing radar art, and will attempt to draw conclusions about the prospects of this technology. Some of the results achieved to date by many of the laboratories and organizations engaged in this work are covered, including some work that is up to 20 years old, as well as work accomplished in recent weeks. The spectrum of results is quite varied, ranging from the disappointing to the encouraging. Identification of some of the factors leading to or limiting success in this area and definition of some likely prospects for further application are attempted. Finally, some of the research efforts that will be required to fully evaluate the feasibility of these hoped-for applications are described.

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PREFACE

The work reported here was prepared for the Advanced Research Projects Agency in partial response to the task order entitled "Ultra-Wideband Radar Technology Evaluation." The material is based on a briefing presented to an unclassified audience at the SPIE meeting on "Underground and Obscured Target Imaging and Detection," April 15-16, 1993, in Orlando, Florida.

ABSTRACT

This paper focuses on some of the work forming the background of today's state of the ground probing radar art, and will attempt to draw conclusions about the prospects of this technology. We cover some of the results achieved to date by many of the laboratories and organizations engaged in this work, including some work that is up to 20 years old, as well as work accomplished in the last few weeks. The spectrum of results is quite varied, ranging from the disappointing to the encouraging. We attempt to identify some of the factors leading to or limiting success in this area and define some likely prospects for further application. Finally, we describe some of the research efforts that will be required to fully evaluate the feasibility of these hoped-for applications.

CONTENTS

PERSPECTIVE ON UNDERGROUND AND OBSCURED TARGET DETECTION AND IMAGING

Background and Prospects for Ground Probing Radar

- What results have been achieved to date?
  - Many Labs and Organizations
- What factors appear to govern GPR performance?
- What are the likeliest prospects for further application?
- What research is needed to define the feasibility of these applications?

BACKGROUND AND PROSPECTS FOR GROUND PROBING RADAR

This briefing focuses on some of the work forming the background of today's state of the ground probing radar art, and will attempt to draw conclusions about the prospects of this technology.

We will cover some of the results achieved to date by many of the laboratories and organizations engaged in this work, including some work that is up to 20 years old, as well as work accomplished in the last few weeks. The spectrum of results is quite varied, ranging from the disappointing to the encouraging. We will attempt to identify some of the factors leading to or limiting success in this area and define some likely prospects for further application.

Finally, we will describe some of the research efforts that will be required to fully evaluate the feasibility of these hoped-for applications.

Some Current Results with GPR

- LL: Tunnel Penetration Experiments
- NASA: Space-Based SAR
- Army/Navy: Buried Ordnance Detection
- Commercial Utility Detection
- Microwave Holography Results

SOME CURRENT RESULTS WITH GPR

Although it would be impossible to cover the full range of experimental work in ground penetrating radar over the last two decades, the examples shown here represent a reasonable sampling. All of these examples represent unclassified work, whether done in commercial or government laboratories.

To begin, we will mention work done by Lincoln Laboratory in measuring the signal propagation loss at UHF through soil and rock. Other work is the well known and spectacular results achieved by NASA using SEASAT and SIR-A orbital radar. The Services have collaborated in the development of technology intended to detect unexploded ordnance. Commercial concerns have attempted to develop a capability to detect and map subsurface utility lines, such as gas, water and power. Finally, we will mention some very recent and thought-provoking results obtained using microwave holography at Pacific Northwest Laboratory.

Rock Penetration Experiments

Gold Hill, Colorado 1982

- Tests focused on a specific airborne radar system:
  - Radar from Applied Sciences, Inc.
  - Tests instrumented and reported by Lincoln Laboratory

- Attempt to detect tunnel in hard rock at depths up to 50 metres
  - Abandoned gold mine adit

- Helicopter-borne "probing" radar
  - 250-750 MHz, FM-CW
  - Low-gain antenna
  - Low-radiated power (1W)

- Measurements confined to one-way path losses.
  - Measured losses: 4-8 dB/meter
  - No phase defect measured (relevant to imaging)

- Radar performance in mine tunnel detection was estimated by LL from measured losses:
  - Based on characteristics of ASI radar
  - Up to 3 meters (real time)
  - not more than 5-10 meters with full post detection signal processing

- Tests consistent with conclusion that UHF is not useful for more than a few meters penetration, except in unusual conditions (hyperarid or frozen rock)

ROCK PENETRATION EXPERIMENTS
GOLD HILL, COLORADO 1982

These tests were conducted in 1982 to evaluate a specific airborne radar system, developed by Applied Sciences in the ground penetration role. The tests were conducted and described by Lincoln Laboratory.

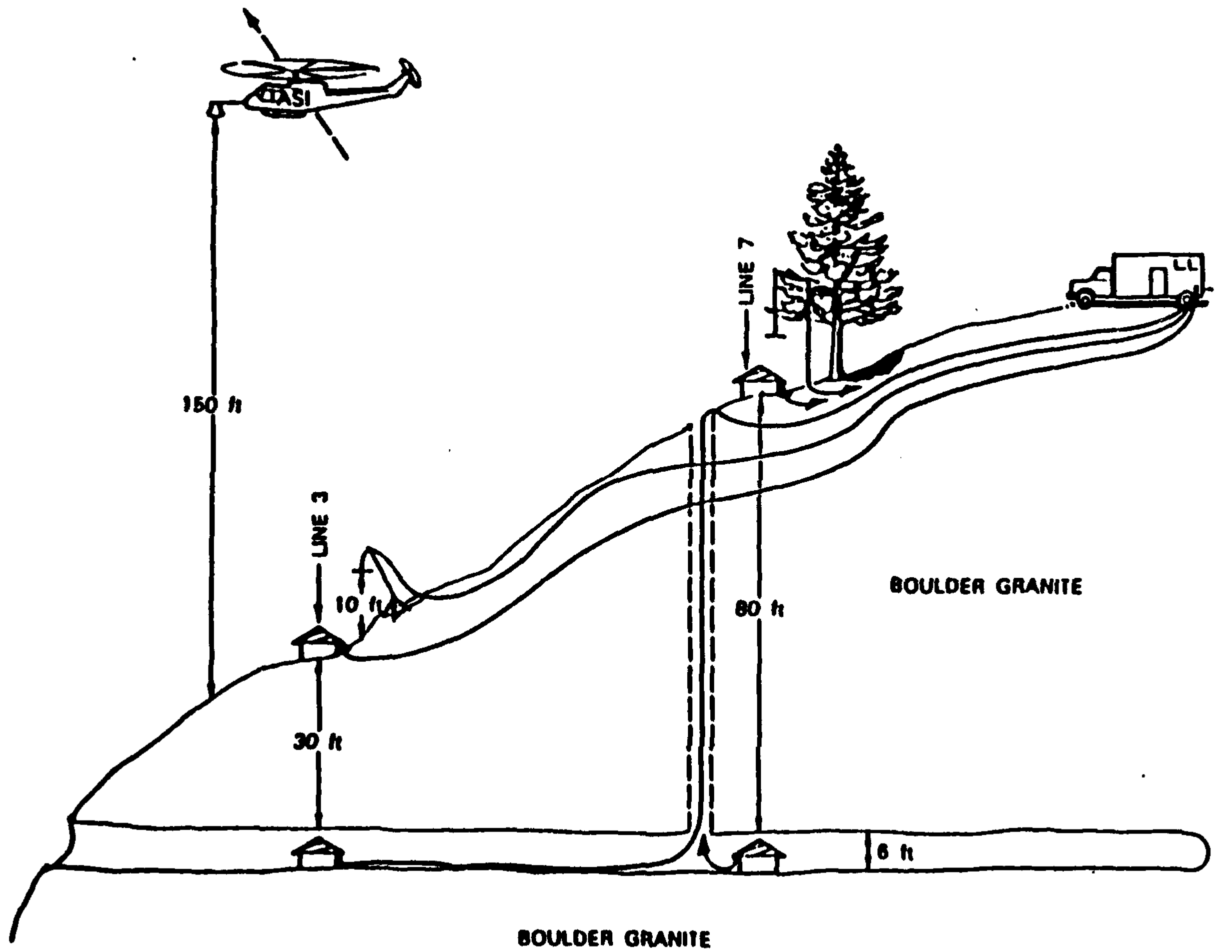
The goal was the detection of existing abandoned gold-mine tunnels at depths of up to 50 meters in hard rock. The system was a helicopter-borne probing radar operating in the 250-750 MHz band.

The actual measurements were limited to measurements of one-way path loss using an incoherent data collection system. This system was capable of determining losses in the range of 4-8 dB, but was not able to provide measurements of phase defect, and thus could not predict the feasibility of radar imaging at the frequencies chosen.

Post-experiment analyses by Lincoln indicated that, even if images could be obtained, the radar would be limited to depths of not more than a few meters in the ground structures tested. Attempting greater penetration would be feasible only in extremely low-loss soils, such as hyperarid or frozen rock.

ROCK PENETRATION MEASUREMENT CONFIGURATION

"HAZEL A" MINESHAFT



LL Test Setup at Gold Hill for Differential Path Loss from the ASI Airborne Transmitter and from and LL Hangman Dipole

ROCK PENETRATION MEASUREMENT CONFIGURATION

"HAZEL A" MINESHAFT

This illustrates the experimental configuration used in the LL evaluation. In many ways this also illustrates the goal of much ground penetration research. We would like to uncover activities being carried out at significant depths, using a non-intrusive airborne platform, obtaining a real-time picture of subsurface targets and activities.

Space-Based SAR

- JPL, USGS, et al
- SEASAT, SIR-A, SIR-B
  - L-band radar
  - 20-40 meter resolution
- Arid Regions:
  - Mojave Desert, Saudi Arabia, Egyptian Sahara
- Highly favorable conditions:
  - Low moisture content--Low attenuation
  - Fine grain sizes--Low scattering
  - Low clay content--Little adsorbed water
  - smooth surface, sparse vegetation--Low surface clutter
  - Thin masking layer
  - Rough contrasting buried surfaces
- Subsurface imaging demonstrated to maximum of 2-3 meters.
  - < 1-1.5 meters typical of results reported

SPACE-BASED SAR

Most of this audience is familiar with the results obtained by NASA and JPL in detecting geologic features buried under sand in the Egyptian and Saudi deserts. What deserves to be mentioned as well is the work done by USGS scientists in telling us exactly what circumstances were required to achieve the images displayed.

These images were obtained using L-band orbital SAR: SEASAT, SIR-A and SIR-B. The resolution of these systems is 20-40 meters, depending on grazing angle.

All of the penetration results were obtained in arid regions under conditions that turned out to be highly favorable for subsurface radar imaging. Some of these factors include low moisture content, leading to low soil conductivity. In addition, the clay content of the soil is low, so what water was present was not effective at binding to clay particles. The fact that grain size is quite small limits losses due to scattering and limits clutter due to backscattering in the sand medium. The surface was smooth, which also minimized backscattering that could compete with the penetrating radar signature. The underlying surface, by contrast, was extremely rough, so that it efficiently scattered back to the radar. For all this, penetrating radar effectiveness was limited to 2-3 meters, with depths of 1.5 meters being more typical of the results reported.

Buried Ordnance Detection

- Corps of Engineers/ Naval EOTC--Indian Head
  - Gregory Hogan (Geo-Centers), 1988
- 6-inch to 14-foot depths
- 155 mm projectile to 500-lb bombs
- Pit excavated in clay, backfilled with sand

BURIED ORDNANCE DETECTION

The detection of unexploded ordnance is a prerequisite to disposal, both in former battlefields and in domestic military test and training ranges. In an effort to evaluate radar as a detection tool, the Army Corps of Engineers and the Naval Explosive Ordnance Technology Development Center collaborated in arranging tests of a Geo-Centers subsurface probing radar at the EODTC range in Indian Head. This range consists of a range of ordnance, from small mortar rounds to MK 80 series bombs, buried at depths from 6 inches to 14 feet.

For purposes of this test, the native clay was excavated from a pit 45 by 15 feet in dimension, which was backfilled with sand. This concession to the losses of clay soil should be borne in mind when we attempt to extrapolate these and similar results.

Commercial Utility Applications

- Richards and Anderson, 1978

- Holography on a field site
  - 2 by 2 meter scanned aperture
  - 950 MHz CW
  - Cross-polarized receiver
  - Intensive data and image processing

- Uncontrolled soil conditions
  - British residential area
  - Moisture, composition arbitrary

- Limited target depths
  - surface to 0.25 meters

COMMERCIAL UTILITY APPLICATIONS

Although fifteen years old, this research is a good example of both holography as applied to subsurface probing, and the limitations imposed by natural soil materials. In this work, Richards and Anderson constructed a 2-meter scanned aperture above the site of a gas delivery pipe. The system was a CW radar operating at 950 MHz, using a cross-polarized radar system and intensive post processing of the images.

Unlike the work mentioned above, which was conducted in an environment of uniform sand, this work was performed through uncontrolled native soil, whose composition and moisture content were not reported. In this case recognizable image results were obtained only down to depths of 0.25 meters. Clearly, soil conditions will govern the performance of ground penetrating radar.

Subsurface Microwave Holography

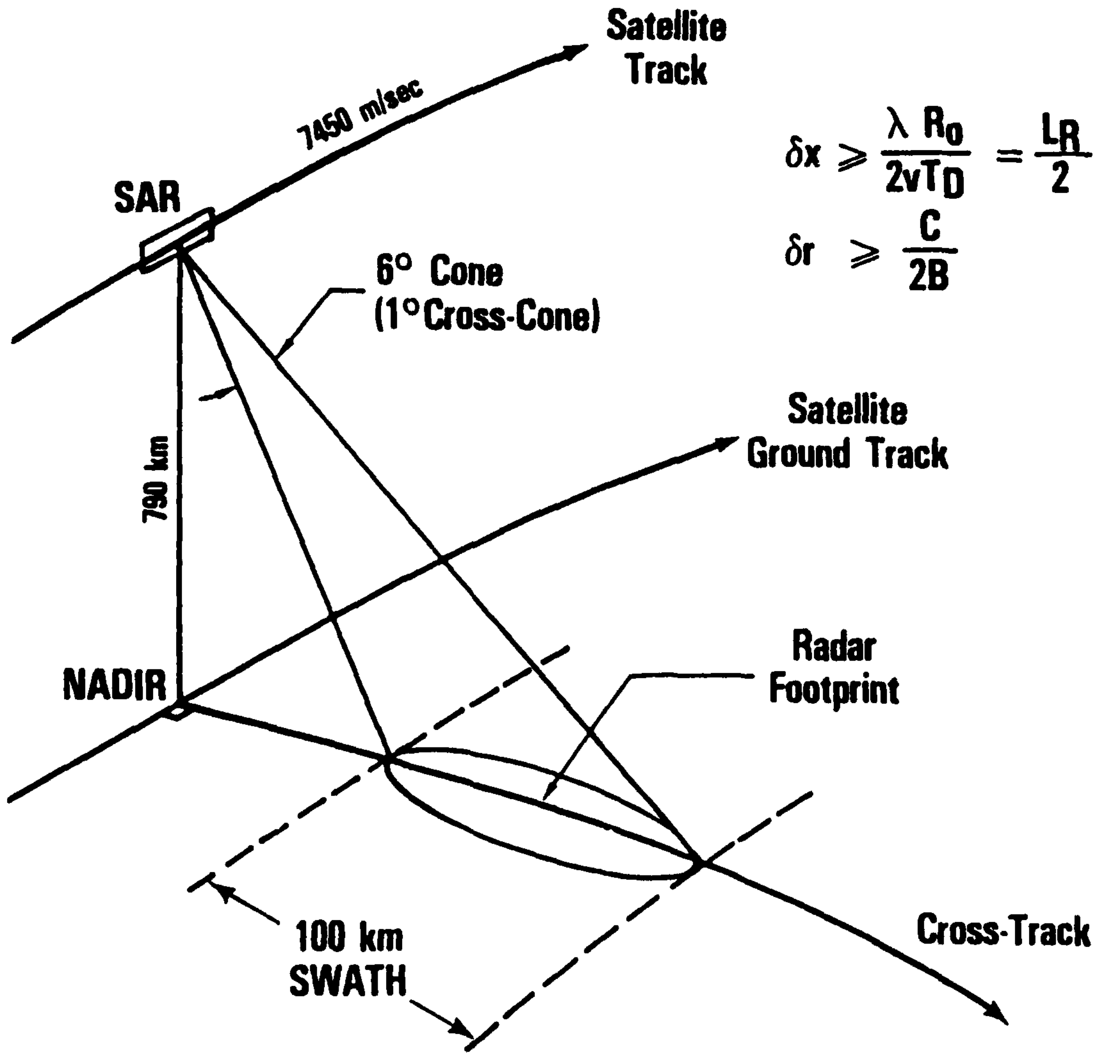
- Battelle/PNL
  - Work in progress, Dale Collins, P.I.
- 100% Bandwidth
  - 2.5-7.5 GHz
  - 3.5-10.5 GHz
- 0.5-1 inch resolution
  - 0.5 meter depth
  - "Wet" sand-- @ 20 dB/meter
- 1 by 1 meter scanned aperture
  - Laboratory conditions
  - may indicate feasibility of scaling

SUBSURFACE MICROWAVE HOLOGRAPHY

Like the work described preceding, this uses holographic techniques to image subsurface objects. These results, however, are new and as yet unpublished. What is remarkable about them is the wide bandwidth and use of relatively high microwave frequencies. These factors lead to resolutions of less than one inch. One factor leading to such good resolution is that the medium is a uniform sand which should show very little scattering, although losses are not negligible at 20 dB/meter.

In this case the scanned aperture is 1 by 1 meter. Although this is less aperture than the previous example by a factor of two, the higher frequency provides even better resolution.

SAR IMAGING GEOMETRY



$$\delta x \geqslant \frac{\lambda R_0}{2vT_D} = \frac{L_R}{2}$$

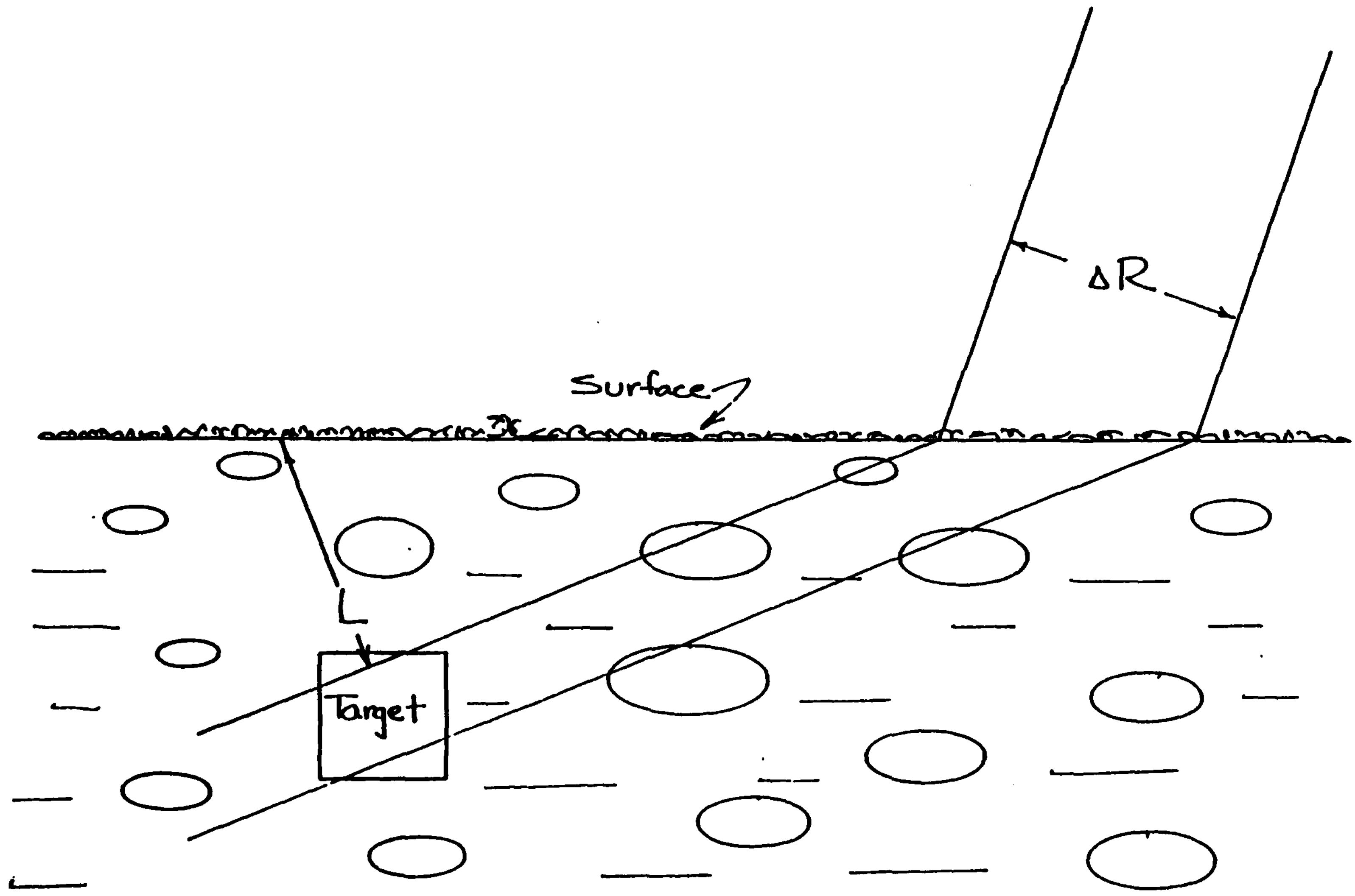
$$\delta r \geqslant \frac{C}{2B}$$

(after JPL)

SAR IMAGING GEOMETRY

This sketch illustrates how a synthetic aperture radar forms its resolution cells. The cross-track resolution comes from the bandwidth of the waveform, while the along-track resolution is derived from the phase history of scatterers as the satellite passes through its closest point of approach. The resulting three-dimensional radar resolution cells have little or no resolution in the vertical plane, as is illustrated on the next slide.

SUBSURFACE SAR RESOLUTION CELL



SUBSURFACE SAR RESOLUTION CELL

This illustration shows the structure of the SAR resolution cell above and below the surface. The point is that everything in the cell appears at a single image pixel. Thus, any subsurface target of interest, which may be heavily attenuated by soil losses, must compete not only with clutter objects at shallower depths, but also with surface backscatter that is not attenuated at all. This represents a fundamental drawback to the SAR system for underground target detection, and a fundamental advantage to holographic systems, which form true three-dimensional pixels (voxels) that lie completely beneath the surface.

The Propagating Medium is Critical

- The soil medium is characterized by *absorption* and *inhomogeneity*.
  - Both contribute to wave attenuation
- There is wide variation in subsurface attenuation, depending on wavelength, soil type and moisture content.
- Attenuation primarily degrades
  - target S/N, but more critically:
  - target S relative to surface clutter (in SAR imaging systems)
- Soil inhomogeneity and inclusions lead to
  - volume clutter
  - propagation distortions (degrade imaging)
  - scattering and loss of image contrast
  - additional attenuation when grain size > $\lambda/10$

THE PROPAGATING MEDIUM IS CRITICAL

As a propagating medium, soil is characterized by absorption, which transforms RF radiation to local heating, and scattering, which removes energy from propagating plane waves and randomizes it without heating. Both contribute to wave attenuation, although the most severe performance limit may be scattering.

Although radar propagation in the atmosphere is subject to propagation effects, their magnitude is small compared to the impact of subsurface conditions.

The impact of attenuation is primarily on signal to noise ratio, but even more critical is the impact on signal to clutter ratio, when the target is severely attenuated and the clutter is not at all affected. This is the case particularly with SAR imaging systems.

The effect of soil inhomogeneity is more pernicious. Besides volume clutter, soil structure can lead to distorted propagation that degrades imaging, scattering and resulting loss of image contrast, and additional attenuation by scattering energy out of the coherent plane waves upon which current imaging systems depend.

RF Propagation in Soil--Need for Research

- We require a basis for *radar performance prediction.*
  - Attenuation
  - Scattering
- Much electromagnetic work has focused on constitutive parameters:
  - Permittivity (& permeability) as point properties
  - Measured in waveguide apparatus
- Questions of soil structure, inhomogeneity have largely been left to geologists.
  - *These may dominate* detection performance through scattering.
- Many theoretical *treatments* assume weakly-scattering (singly-scattering, tenuous, diaphanous) media with weak attenuation.
- Soil Structure often limited to single statistical parameter
  - assumed isotropic, spatially invariant
- Need for empirical work focusing on wave propagation, as well as on system effectiveness in target detection.

RF PROPAGATION IN SOIL--NEED FOR RESEARCH

Although much work has been done in characterizing the electromagnetic constitutive parameters of bulk soils, and in characterizing soil structures from a geological viewpoint, neither of these approaches fully satisfies the radar system designer, who is seeking a basis for radar performance predictions. If scattering and other inhomogeneous effects are the principal limits to subsurface radar performance, then what is needed is a system for describing the effect of soil structure on wave propagation.

Such theoretical models of propagation in random inhomogeneous media as exist are generally based on weak scattering approximations. Although these models are adequate in describing propagation in thin media, such as a turbulent atmosphere, they hardly apply to dense media such as soils. Moreover, available models are often limited to a single parameter with which to describe soil structure, and this parameter is often constrained to be isotropic and spatially invariant. The development of an adequate and useful theory is likely to be so long in coming that the most fruitful approaches in the near future may by empirical. In general there is a requirement to emphasize work on subsurface wave propagation as well as on system effectiveness.

GPR Success and Failure

- Attempts to apply GPR to date have been mixed. With some exceptions, the factors associated with success tend to be:

  - Surface-Located Radar
  - Shallow Target Depths beneath planar surface
    - Low Attenuation
    - Little Beam-Spreading despite large beamwidths
  - Known Targets
    - Utilities
    - Waste/Hazmat Containers
    - Targets $\geq$ 1 meter
    - System Demonstrations on Mine-sized Targets
  - Small Search Volume

- The factors associated with disappointments tend to be:

  - Airborne Radar (SB SAR excepted)
  - Deep Targets / rough (mountainous) terrain
  - Longer Ranges
  - Larger Beam-Spread / poorer resolution
  - Non-specific Targets
  - Larger Search Volumes

GPR SUCCESS AND FAILURE

Attempts to develop useful detection systems using ground probing radar have been very mixed. An examination of results obtained to date, however, shows a broad demarcation between "successes" and "failures." The distinctions are not absolute, but with some exceptions the factors associated with perceived success may be: The use of a surface radar over a planar surface to detect objects whose characteristics are known at relatively shallow depths. A key requirement is that the search volume be heavily restricted.

By contrast, the factors associated with disappointment would seem to be: Attempts to use airborne radar systems to detect general or unknown targets buried deeply in rough terrain, particularly when the search volume is large and the radar system cannot be cued by other systems.

Prospects for GPR Application (1)
Large-Scale Targets

- Subsurface targets are embedded in a lossy, inhomogeneous random medium of arbitrary statistics.
- Long wavelengths can reduce absorption and scattering from inhomogeneities
- Imaging is probably necessary to reduce false alarms
  - Pixel size < target dimensions
  - Practically, pixel size ≥ wavelength
  - Bandwidth, angle limits
- Exploiting long wavelengths implies targets must be large
- Recognition further enhanced when target size >> scale of soil inhomogeneity
  - Spatial filtering issues

PROSPECTS FOR GPR APPLICATION (1)

LARGE-SCALE TARGETS

The applications for radar in subsurface target detection seem to fall into two broad categories, characterized by the scale of the system, target, terrain structures and search volume. The argument for the *large-scale case* proceeds as follows: We know that long wavelengths can reduce absorption and scattering from loss mechanisms and soil inhomogeneities. We also postulate that imaging is necessary to reduce false alarms. Since resolution is limited by bandwidth and angle limits, and ultimately by average wavelength, the use of long wavelengths implies that the targets sought must be large. (Ideally, the target should be larger than the scale of soil structures, to allow spatial filtering techniques to be of use in target discrimination.)

Prospects for GPR Application (2)
Small-Scale Targets

- Small targets (e.g. mines, caches) also hard to distinguish from clutter.
  - Imaging equally important
- Much finer resolution is needed
  - Wider bandwidths require higher overall frequency range.
- Feasible targets are likely to be shallow--e.g. land mines.
- It will be difficult and perhaps pointless to attempt to develop a single system to cover both large/deep targets and small/shallow targets.
  - Frequency ranges are different
  - Antenna sizes will be different
  - Operational concepts may be inconsistent

PROSPECTS FOR GPR APPLICATION (2)

SMALL-SCALE TARGETS

Small scale targets, such as mines or weapons caches, are also hard to distinguish from clutter, so imaging will be important to systems designed to detect them as well. At this smaller scale, much finer resolution will be needed, implying the need for wider bandwidths and ultimately higher overall frequencies. On the other hand, feasible targets will tend to be shallow, like land mines, so that attenuation and scattering may be more acceptable over shorter propagation paths.

In comparing these two scales of system application, it should be apparent that it will be difficult and perhaps pointless to attempt to develop a single system for the detection of both large/deep targets and small/shallow targets. The wide difference in frequency range not only implies a large range in system electronics, but also in the size of the relevant antenna systems. Operation concepts are also likely to differ. The large scale system may be adaptable to an aircraft, while the small-scale system may need to be placed on a ground vehicle.

GPR Development Program Objectives

- Determine feasibility and limitations of subsurface radar imaging
  - Imaging is likely to be the key to target recognition and characterization
  - There is more than one imaging approach (e.g. SAR, Holography)
  - What is the optimum trade-off between penetration and resolution for different sizes and types of targets?

- Develop/exploit appropriate testbed and data collection system to conduct subsurface measurements over a range of wavelengths and resolutions
  - Focus on essential propagation and clutter phenomenology, as well as "target truth" rather than the characteristics of any specific radar system.
  - Polarimetric flexibility is likely to be important.

- Identify practical, *feasible target set relevant to national security requirements*
  - range of sizes and dimensions
  - range of soil contexts
  - ancillary signature elements: construction, burial signatures, context disturbance

- Develop appropriate detection algorithms to exploit data at varying resolutions

- Exploit possible fusion/coordination with other sensors
  - fusion to enhance ROC
  - coordination to limit search areas

- Media propagation effects dominate GPR performance. Exhaustive experiments characterizing propagation in the full range of media types will be costly.
  - Consider scaled experiments to investigate propagation effects and aid in planning of *full-scale measurements.*

GPR DEVELOPMENT PROGRAM OBJECTIVES

A possible program for the development of ground probing radar should have several short- and long-range objectives. To begin with, we must ascertain the ultimate feasibility and limitations of radar imaging in a subsurface environment. This is important because imaging is likely to be the key to target discrimination. Although there is more than one imaging paradigm--i.e., SAR vs holography, they share a common constraint relating resolution to bandwidth. This leads to a need to determine the range of optimum trade-offs between penetration and resolution for different target types.

Determining this probably cannot be done theoretically. We will therefore require an appropriate testbed and data collection system to conduct an empirical study of subsurface phenomenology over a wide range of resolutions and wavelengths.

At the same time, if we plan to exploit GPR in a national security role, we need to identify a feasible target set. Data from targets and the measurements of the test asset can be combined to develop appropriate target detection algorithms. If at all possible, GPR should be designed to exploit data from other sensors. Detection performance will be enhanced by suitable sensor fusion, but even the ability to limit search area would be invaluable.

Because an exhaustive set of experiments characterizing propagation in the full set of media types will be very costly, some consideration should be given to whether scaled experiments could be of use in investigating propagation effects and in planning full-scale data collection campaigns.

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